



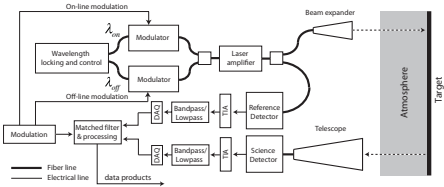
A Comparison of Potential IM-CW Lidar Modulation Techniques for ASCENDS CO₂ Column Measurements from Space

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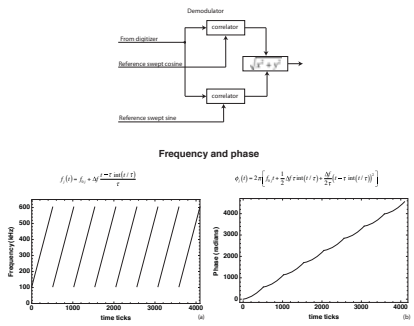
Abstract

Global atmospheric carbon dioxide (CO₂) measurements through the Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS) decadal survey recommended space mission are critical for improving our understanding of CO₂ sources and sinks. IM-CW (Intensity Modulated Continuous Wave) lidar techniques are investigated as a means of facilitating CO₂ measurements from space to meet the ASCENDS science requirements. In previous laboratory and flight experiments we have successfully used linear sweep frequency modulation to discriminate surface lidar returns from intermediate aerosol and cloud contamination. Furthermore, high accuracy and precision ranging to the surface as well as to the top of intermediate clouds, which is a requirement for the inversion of the CO₂ column-ratio ratio from the instrument optical depth measurements, has been demonstrated with the linear sweep frequency modulation technique. We are concurrently investigating advanced techniques to help improve the auto-correlation properties of the transmitted waveform implemented through physical hardware to make cloud rejection more robust in special restricted scenarios. Several different carrier based modulation techniques are compared including orthogonal linear sweep, orthogonal non-linear sweep, and Binary Phase Shift Keying (BPSK). Techniques are investigated that reduce or eliminate sidelobes. These techniques have excellent auto-correlation properties while possessing a finite bandwidth (by way of a new cyclic digital filter), which will reduce bias error in the presence of multiple scatterers. Our analyses show that the studied modulation techniques can increase the accuracy of CO₂ column measurements from space. A comparison of various properties such as Signal to Noise (SNR) and time-bandwidth product are discussed.

Instrument Concept



Linear Frequency Modulation



Example start frequencies for orthogonal 8 sweep system with N=4096

$$f_{k=0} = 2.78 \times (1512/2000) = 2.0808 \text{ MHz}, f_{k=1} = 2.0808 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2.0808 \text{ MHz} + 108.368 \text{ MHz} = 108.368 \text{ MHz}$$

$$f_{k=2} = 108.368 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 108.368 \text{ MHz} + 108.368 \text{ MHz} = 216.736 \text{ MHz}$$

$$f_{k=3} = 216.736 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 216.736 \text{ MHz} + 108.368 \text{ MHz} = 325.104 \text{ MHz}$$

$$f_{k=4} = 325.104 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 325.104 \text{ MHz} + 108.368 \text{ MHz} = 433.472 \text{ MHz}$$

$$f_{k=5} = 433.472 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 433.472 \text{ MHz} + 108.368 \text{ MHz} = 541.840 \text{ MHz}$$

$$f_{k=6} = 541.840 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 541.840 \text{ MHz} + 108.368 \text{ MHz} = 650.208 \text{ MHz}$$

$$f_{k=7} = 650.208 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 650.208 \text{ MHz} + 108.368 \text{ MHz} = 758.576 \text{ MHz}$$

$$f_{k=8} = 758.576 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 758.576 \text{ MHz} + 108.368 \text{ MHz} = 866.944 \text{ MHz}$$

$$f_{k=9} = 866.944 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 866.944 \text{ MHz} + 108.368 \text{ MHz} = 975.312 \text{ MHz}$$

$$f_{k=10} = 975.312 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 975.312 \text{ MHz} + 108.368 \text{ MHz} = 1083.680 \text{ MHz}$$

$$f_{k=11} = 1083.680 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 1083.680 \text{ MHz} + 108.368 \text{ MHz} = 1192.048 \text{ MHz}$$

$$f_{k=12} = 1192.048 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 1192.048 \text{ MHz} + 108.368 \text{ MHz} = 1300.416 \text{ MHz}$$

$$f_{k=13} = 1300.416 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 1300.416 \text{ MHz} + 108.368 \text{ MHz} = 1408.784 \text{ MHz}$$

$$f_{k=14} = 1408.784 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 1408.784 \text{ MHz} + 108.368 \text{ MHz} = 1517.152 \text{ MHz}$$

$$f_{k=15} = 1517.152 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 1517.152 \text{ MHz} + 108.368 \text{ MHz} = 1625.520 \text{ MHz}$$

$$f_{k=16} = 1625.520 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 1625.520 \text{ MHz} + 108.368 \text{ MHz} = 1733.888 \text{ MHz}$$

$$f_{k=17} = 1733.888 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 1733.888 \text{ MHz} + 108.368 \text{ MHz} = 1842.256 \text{ MHz}$$

$$f_{k=18} = 1842.256 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 1842.256 \text{ MHz} + 108.368 \text{ MHz} = 1950.624 \text{ MHz}$$

$$f_{k=19} = 1950.624 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 1950.624 \text{ MHz} + 108.368 \text{ MHz} = 2058.992 \text{ MHz}$$

$$f_{k=20} = 2058.992 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2058.992 \text{ MHz} + 108.368 \text{ MHz} = 2167.360 \text{ MHz}$$

$$f_{k=21} = 2167.360 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2167.360 \text{ MHz} + 108.368 \text{ MHz} = 2275.728 \text{ MHz}$$

$$f_{k=22} = 2275.728 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2275.728 \text{ MHz} + 108.368 \text{ MHz} = 2384.096 \text{ MHz}$$

$$f_{k=23} = 2384.096 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2384.096 \text{ MHz} + 108.368 \text{ MHz} = 2492.464 \text{ MHz}$$

$$f_{k=24} = 2492.464 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2492.464 \text{ MHz} + 108.368 \text{ MHz} = 2600.832 \text{ MHz}$$

$$f_{k=25} = 2600.832 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2600.832 \text{ MHz} + 108.368 \text{ MHz} = 2709.200 \text{ MHz}$$

$$f_{k=26} = 2709.200 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2709.200 \text{ MHz} + 108.368 \text{ MHz} = 2817.568 \text{ MHz}$$

$$f_{k=27} = 2817.568 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2817.568 \text{ MHz} + 108.368 \text{ MHz} = 2925.936 \text{ MHz}$$

$$f_{k=28} = 2925.936 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 2925.936 \text{ MHz} + 108.368 \text{ MHz} = 3034.304 \text{ MHz}$$

$$f_{k=29} = 3034.304 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 3034.304 \text{ MHz} + 108.368 \text{ MHz} = 3142.672 \text{ MHz}$$

$$f_{k=30} = 3142.672 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 3142.672 \text{ MHz} + 108.368 \text{ MHz} = 3251.040 \text{ MHz}$$

$$f_{k=31} = 3251.040 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 3251.040 \text{ MHz} + 108.368 \text{ MHz} = 3359.408 \text{ MHz}$$

$$f_{k=32} = 3359.408 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 3359.408 \text{ MHz} + 108.368 \text{ MHz} = 3467.776 \text{ MHz}$$

$$f_{k=33} = 3467.776 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 3467.776 \text{ MHz} + 108.368 \text{ MHz} = 3576.144 \text{ MHz}$$

$$f_{k=34} = 3576.144 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 3576.144 \text{ MHz} + 108.368 \text{ MHz} = 3684.512 \text{ MHz}$$

$$f_{k=35} = 3684.512 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 3684.512 \text{ MHz} + 108.368 \text{ MHz} = 3792.880 \text{ MHz}$$

$$f_{k=36} = 3792.880 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 3792.880 \text{ MHz} + 108.368 \text{ MHz} = 3901.248 \text{ MHz}$$

$$f_{k=37} = 3901.248 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 3901.248 \text{ MHz} + 108.368 \text{ MHz} = 4009.616 \text{ MHz}$$

$$f_{k=38} = 4009.616 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4009.616 \text{ MHz} + 108.368 \text{ MHz} = 4117.984 \text{ MHz}$$

$$f_{k=39} = 4117.984 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4117.984 \text{ MHz} + 108.368 \text{ MHz} = 4226.352 \text{ MHz}$$

$$f_{k=40} = 4226.352 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4226.352 \text{ MHz} + 108.368 \text{ MHz} = 4334.720 \text{ MHz}$$

$$f_{k=41} = 4334.720 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4334.720 \text{ MHz} + 108.368 \text{ MHz} = 4443.088 \text{ MHz}$$

$$f_{k=42} = 4443.088 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4443.088 \text{ MHz} + 108.368 \text{ MHz} = 4551.456 \text{ MHz}$$

$$f_{k=43} = 4551.456 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4551.456 \text{ MHz} + 108.368 \text{ MHz} = 4659.824 \text{ MHz}$$

$$f_{k=44} = 4659.824 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4659.824 \text{ MHz} + 108.368 \text{ MHz} = 4768.192 \text{ MHz}$$

$$f_{k=45} = 4768.192 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4768.192 \text{ MHz} + 108.368 \text{ MHz} = 4876.560 \text{ MHz}$$

$$f_{k=46} = 4876.560 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4876.560 \text{ MHz} + 108.368 \text{ MHz} = 4984.928 \text{ MHz}$$

$$f_{k=47} = 4984.928 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 4984.928 \text{ MHz} + 108.368 \text{ MHz} = 5093.296 \text{ MHz}$$

$$f_{k=48} = 5093.296 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 5093.296 \text{ MHz} + 108.368 \text{ MHz} = 5201.664 \text{ MHz}$$

$$f_{k=49} = 5201.664 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 5201.664 \text{ MHz} + 108.368 \text{ MHz} = 5310.032 \text{ MHz}$$

$$f_{k=50} = 5310.032 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 5310.032 \text{ MHz} + 108.368 \text{ MHz} = 5418.400 \text{ MHz}$$

$$f_{k=51} = 5418.400 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 5418.400 \text{ MHz} + 108.368 \text{ MHz} = 5526.768 \text{ MHz}$$

$$f_{k=52} = 5526.768 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 5526.768 \text{ MHz} + 108.368 \text{ MHz} = 5635.136 \text{ MHz}$$

$$f_{k=53} = 5635.136 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 5635.136 \text{ MHz} + 108.368 \text{ MHz} = 5743.504 \text{ MHz}$$

$$f_{k=54} = 5743.504 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 5743.504 \text{ MHz} + 108.368 \text{ MHz} = 5851.872 \text{ MHz}$$

$$f_{k=55} = 5851.872 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 5851.872 \text{ MHz} + 108.368 \text{ MHz} = 5960.240 \text{ MHz}$$

$$f_{k=56} = 5960.240 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 5960.240 \text{ MHz} + 108.368 \text{ MHz} = 6068.608 \text{ MHz}$$

$$f_{k=57} = 6068.608 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 6068.608 \text{ MHz} + 108.368 \text{ MHz} = 6176.976 \text{ MHz}$$

$$f_{k=58} = 6176.976 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 6176.976 \text{ MHz} + 108.368 \text{ MHz} = 6285.344 \text{ MHz}$$

$$f_{k=59} = 6285.344 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 6285.344 \text{ MHz} + 108.368 \text{ MHz} = 6393.712 \text{ MHz}$$

$$f_{k=60} = 6393.712 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 6393.712 \text{ MHz} + 108.368 \text{ MHz} = 6502.080 \text{ MHz}$$

$$f_{k=61} = 6502.080 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 6502.080 \text{ MHz} + 108.368 \text{ MHz} = 6610.448 \text{ MHz}$$

$$f_{k=62} = 6610.448 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 6610.448 \text{ MHz} + 108.368 \text{ MHz} = 6718.816 \text{ MHz}$$

$$f_{k=63} = 6718.816 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 6718.816 \text{ MHz} + 108.368 \text{ MHz} = 6827.184 \text{ MHz}$$

$$f_{k=64} = 6827.184 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 6827.184 \text{ MHz} + 108.368 \text{ MHz} = 6935.552 \text{ MHz}$$

$$f_{k=65} = 6935.552 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 6935.552 \text{ MHz} + 108.368 \text{ MHz} = 7043.920 \text{ MHz}$$

$$f_{k=66} = 7043.920 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 7043.920 \text{ MHz} + 108.368 \text{ MHz} = 7152.288 \text{ MHz}$$

$$f_{k=67} = 7152.288 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 7152.288 \text{ MHz} + 108.368 \text{ MHz} = 7260.656 \text{ MHz}$$

$$f_{k=68} = 7260.656 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 7260.656 \text{ MHz} + 108.368 \text{ MHz} = 7369.024 \text{ MHz}$$

$$f_{k=69} = 7369.024 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 7369.024 \text{ MHz} + 108.368 \text{ MHz} = 7477.392 \text{ MHz}$$

$$f_{k=70} = 7477.392 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 7477.392 \text{ MHz} + 108.368 \text{ MHz} = 7585.760 \text{ MHz}$$

$$f_{k=71} = 7585.760 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 7585.760 \text{ MHz} + 108.368 \text{ MHz} = 7694.128 \text{ MHz}$$

$$f_{k=72} = 7694.128 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 7694.128 \text{ MHz} + 108.368 \text{ MHz} = 7802.496 \text{ MHz}$$

$$f_{k=73} = 7802.496 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 7802.496 \text{ MHz} + 108.368 \text{ MHz} = 7910.864 \text{ MHz}$$

$$f_{k=74} = 7910.864 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 7910.864 \text{ MHz} + 108.368 \text{ MHz} = 8019.232 \text{ MHz}$$

$$f_{k=75} = 8019.232 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8019.232 \text{ MHz} + 108.368 \text{ MHz} = 8127.600 \text{ MHz}$$

$$f_{k=76} = 8127.600 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8127.600 \text{ MHz} + 108.368 \text{ MHz} = 8235.968 \text{ MHz}$$

$$f_{k=77} = 8235.968 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8235.968 \text{ MHz} + 108.368 \text{ MHz} = 8344.336 \text{ MHz}$$

$$f_{k=78} = 8344.336 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8344.336 \text{ MHz} + 108.368 \text{ MHz} = 8452.704 \text{ MHz}$$

$$f_{k=79} = 8452.704 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8452.704 \text{ MHz} + 108.368 \text{ MHz} = 8561.072 \text{ MHz}$$

$$f_{k=80} = 8561.072 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8561.072 \text{ MHz} + 108.368 \text{ MHz} = 8669.440 \text{ MHz}$$

$$f_{k=81} = 8669.440 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8669.440 \text{ MHz} + 108.368 \text{ MHz} = 8777.808 \text{ MHz}$$

$$f_{k=82} = 8777.808 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8777.808 \text{ MHz} + 108.368 \text{ MHz} = 8886.176 \text{ MHz}$$

$$f_{k=83} = 8886.176 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8886.176 \text{ MHz} + 108.368 \text{ MHz} = 8994.544 \text{ MHz}$$

$$f_{k=84} = 8994.544 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 8994.544 \text{ MHz} + 108.368 \text{ MHz} = 9102.912 \text{ MHz}$$

$$f_{k=85} = 9102.912 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 9102.912 \text{ MHz} + 108.368 \text{ MHz} = 9211.280 \text{ MHz}$$

$$f_{k=86} = 9211.280 \text{ MHz} + \frac{18}{2.78 \times (1512/2000)} = 9211.280 \text{ MHz} + 108.368 \text{ MHz}$$